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The human cost of global warming: Deadly landslides and their triggers (1995-2014)

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ABSTRACT

Worldwide, landslides incur catastrophic and significant economic and human losses. Previous studies have characterized the patterns in landslides' fatalities, from all kind of triggering causes, at a continental or global scale, but they were based on data from periods of less than 10 years. The research herein presented hypothesize that climate change associated with extreme rainfall and population distribution is contributing to a higher number of deadly landslides worldwide. This study maps spatially identifies deadly landslides in 128 countries and it encompasses their role, for a 20 years' period January/1995 to December/2014, considered representative for establishing a relationship between landslides and their meteorological triggers. A database of georeferenced landslides, their date, and casualties' information, duly validated, was implemented. A hot spot analysis for the daily record of landslide locations was performed, as well as a percentile-based approach to evaluate the trend of extreme rainfall events for each occurrence. The relationship between casualty, population distribution, and rainfall was also evaluated. For 20 years, 3876 landslides caused a total of 163,658 deaths and 11,689 injuries globally. They occurred most frequently between June and December in the Northern Hemisphere, and between December and February in the Southern Hemisphere. A significant global rise in the number of deadly landslides and hotspots across the studied period was observed. Analysis of daily rainfall confirmed that more than half of the events were in areas exposed to the risk of extreme rainfall. The relationships established between extreme rainfall, population distribution, seasonality, and landslides provide a useful basis for efforts to model the adverse impacts of extreme rainfall due to climate change and human activities and thus contribute towards a more resilient society.

Keywords

Landslide, Global, Extreme Rainfall, Fatality, Casualty, Hotspot

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Introduction

Landslides are the movements of a mass of rock, debris, and soil down the slopes.[1] The speed at which they occurs can vary considerably, from just a few cm per year up to tens of km/h and the volume of the displaced material can be anywhere from a few tens of m^3 to several km^3.[2] Although water, in the form of rainfall, snow melting or rapid changes in ground water levels, causes the majority of slope failures. There are other significant triggers like earthquakes, volcanic eruptions, human activities and erosion during high water discharges. For shallow landslides, rainfall is the main trigger and they are called rainfall-induced landslides (S1 Terminology, appendix).[3] To predict their probability of occurrence, rainfall intensity-duration relationships have been defined in different geographic regions[4] to derive rainfall thresholds that can be used in daily landslide hazard assessment.[5,6]

Landslides cause significant loss of lives and major economic damages every year in communities globally. Previous studies have reported that the 17 % of fatalities, attributed to natural hazards worldwide, are caused by landslides; being these, in the decade from 1993 to 2002, the 7th biggest killer among natural hazards, causing almost 940 fatalities/year.[7] This figure is however incomplete. The International Disaster Database (EM-DAT) is often used to gather data on landslides losses, but it only register those natural disasters where people have died.[8] Quite often the estimates of death, injury and missing published are approximate, especially when landslides have occurred as secondary hazards (S1 Terminology, appendix) following a primary hazard like earthquake or major storm (S1 Terminology, appendix). This is because some injuries or missing people may transform into deaths and were not inventoried and also because, frequently, the deaths are related only to the primary hazardous event – not the subsequent landslides.[9] To address this problem, researchers have recently sought to characterize

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patterns in the landslides' fatalities, from all causes, at a continental[10] or global scale, albeit for a limited time span of 7[11] and 12 years[9] and also attempted to link them with climate change, mostly through only rainfall data.[12]

The Intergovernmental Panel on Climate Change (IPCC) has suggested an increase in the number of rainfall-induced landslides as a result of the rising of extreme rainfall events (S1 Terminology, appendix) due to climate change, which will have a serious adverse effect on human settlements around the world.[13,14] A recent study has indicated worldwide uneven rainfall. Half of annual rainfall fell in the wettest 12 days[15] and this may have negative implications in the rainfall-triggered landslides worldwide and these events are presently characterized only to a local/regional scales, as mentioned before. It also stated that the increase in rainfall in response to warming occurs, primarily, during events often considered extreme.[15] Therefore, there is a clear need to understand if extreme rainfall will trigger more deadly landslides around the world by analyzing the patterns of landslide distribution globally, especially those located near populated areas, using longer time series data[14] and therefore to publish information to create awareness on this hazard alerting the societies potentially impacted. However, the big limitation in those analyses is represented by the lack of long time series landslide data, due to the fact that landslide casualties have not been systematically recorded in the past.

This study aims to analyze the distribution of deadly landslides around the world by using a 20 years long data series to test our hypothesis that an intensification of extreme rainfall events near presently populated areas may increase the number of deadly landslides. Its specific aims are: (1) to analyze trends in their spatial and 20 years' period of time (1995-2014) distributions and identify hot spots (more recent susceptible areas to events) where landslides have caused

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casualties (death, injury and missing people), thus assessing their severity; and (2) to determine where the incidence of landslide-related casualties is causing more negative impacts in societies globally and where these events may be linked to rainfall triggered landslides.

Material and Methods

Data collection

An up-to-date worldwide landslide database - Global Landslide Database (GLS-DAT), was created for this study to register the casualties caused by landslides in the period analyzed. The information was collected from a number of different sources and corroborated by more than one of those several sources to ensure the data is accurate. Figure 1 and flow chart 1; appendix synthesizes the methodology used to search, update, validate and create the database. A detailed description of the methods is provided in Haque et al[10] and in appendix – S2 Methodology and flow chart 2.

The new database currently contains 3876 landslide events known to have caused casualties between January 1995 and December 2014 in 128 countries. For some events (11.4%), we may not have the exact temporal accuracy (event's exact day). In total 89.6 % of the recorded events (3574) could be validated, and assigned the right location (5 km accuracy), time of occurrence, the number of deaths and serious injuries, and the number of people still missing. Any event, that could not be verified, due to confused reports and the lack of detailed information on a landslide's precise location (such as "multiple locations", "unspecified locations") or missing the location name or date of occurrence, were excluded. If more than one local community was affected by a landslide event, a distinct entry was generated based on its time and spatial

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coordinates. For example, two landslides reported on Jan 10, 2017. One in north (7 killed, 8 PM) and one in south of the town (3 killed at 10 PM), thus two separate records were registered.

Population distribution data for each landslide location were obtained from the LandScan dataset[16] and were extracted using the ArcGIS's spatial analyst tool. The spatial and temporal patterns for the rainfall around the time of each landslide events were generated from satellite-based rainfall data (5 km grid). The data for the total daily rainfall were obtained from the Climate Hazards Group InfraRed Rainfall with Station (CHIRPS).[17]

Spatial analysis

A hot spot analysis was performed for the daily record of landslide locations using the space-time pattern mining tools in ArcGIS (the Emerging Hot Spot Analysis tool, ArcGIS Pro, version 2).[10] All landslide locations over the 20-year period were analyzed to identify position where landslides have occurred in close spatial and temporal proximity. An area of 20 km × 20 km was assigned to each landslide location (based on center on each landslide) and each time step interval was 1-year in duration (S2 Methodology, appendix). Statistically significant spatiotemporal trends were analyzed using the Visualize space-time cube 2D tool.[10]

Statistical analysis

At each landslide location (n=2,866, only non-seismic), extreme rainfall events were quantified in terms of the percentile of daily or multi-day (2 or 3) rainfall accumulations in the corresponding rainfall distribution shown in the database. Maximum 1-day, 2-days, and 3-days accumulations of rainfall were calculated for a 2-week (13 days, plus the day of the landslide)

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window preceding the date of each reported deadly landslide.[12] Rainfall percentiles (50th, 75th, 90th, 95th and 99th) were computed for each of the landslide points. The 20 years' data was used as "baseline" to construct the historical distribution of the rainfall at that location. Then by comparing with the local historical data, we determined whether the 2-week rainfall before the landslide was "extreme" or not (Flow chart 2, appendix).[12]

To determine whether the association between landslides and extreme rainfall was consistent, both events were compared across the first and second decades studied. A Sign test[18] was used to: (i) investigate whether the number of landslides between 1995–2004 and those in 2005–2014 were significantly different, and (ii) determine if the proportion of landslides associated with extreme rainfall events differed between the two decades. The analysis for all combinations of the 50, 90, 95 or 99 percentile values over 1, 2 or 3-days was repeated.[12] We also used Wilcoxon-Mann-Whitney test (10-years versus 10-years two-sample test) and Kruskal-Wallis test (5-year period, separating the 20 years into four samples) in the library (coin), the distribution was estimated via Monte Carlo resampling by setting it to "approximate" (Flow chart 2, appendix).[19]

To visualize the association between rainfall and landslides, the R function "bkde2D" in the library (kernsmooth) was applied to estimate the joint probability density of both events in each region. Casualty, after adjusting for the population distribution, was used as a proxy for landslide impact (LI), while the total amount of rainfall during the 2-weeks before the landslide event was used as a proxy for rainfall intensity (RI). An R function coplot allowed to assess the relationship between casualty and population conditioning on the rainfall values.

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Results

The 3876 landslide events recorded in the GLS-DAT revealed an increasing trend of deadly landslides through the 20 years' period analyzed (Figure 1) which have caused 156,268 fatalities and 177,537 casualties (Table 1), with an average of 8,877 people killed each year. Landslides, responsible for a very high number of fatalities (>10,000) were recorded in several countries - including Venezuela (1999) due to torrential rains caused flash floods and debris flows, Pakistan (2005) because of a massive earthquake, Honduras (2008), and India (2013). Pakistan registered the highest number of deaths exclusively due to landslides (Figure 2; appendix), while Venezuela had the highest recorded fatalities due to simultaneous landslides and floods (Figure 2; appendix). A recent work[9] states that this number is surely underestimated due to events that occurred in remote regions, or that resulted in a small number of fatalities, since they are all less likely to be reported than multi-fatality landslides and/or those that impact urban centers.

The major concentration of deadly landslides (23 %) is spatially located in Southern Pacific while the lowest number is in Africa (4.5 %) (Table 1; appendix), respectively in higher and lower populated areas and also regions highly and lesser affected by atmospheric extreme events - Southern Pacific get extreme rainfall and typhoon events, whereas most parts of Africa are dry. A look at the number of deaths due to landslides, reveals the highest number is registered in South America (23 %), probably due to complex natural disasters like hurricane and a higher population density, while the lowest (0.40 %) is in Western Europe.

For 15% of the recorded landslides, it was possible to identify an unquestionable primary hazard that trigger them, finding that 4.57 % were triggered by storms, 3.43 % by earthquakes, 3.22 %

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by floods, 2.04 % by mining activities, 0.67 % by volcanic eruptions and 0.83 % by other natural or human activities such as coastal erosion, cliff collapses, construction work, embankment collapses, or train derailments (Table 2; appendix), and the remaining of the 85 % were rainfall.

Landslides occurred throughout the year (Figure 3; appendix). Casualties have varied through space and time (Figure 2). The highest number of landslides (including primary hazards) were observed in the months of July, August and September, while most of the fatalities were registered in October (~34 %), December (~22%), and May (13 %), (Figures 4 & 5, appendix). Figure 3A shows the global hotspots for deadly landslides, where they are classified[20] as either sporadic (some of the time step intervals are significantly high), consecutive (a single uninterrupted run of 'hot' time step intervals, comprising less than 90 % of all intervals), persistent (statistically significant hotspot for ninety percent of the time-step intervals) and new (a statistically significant hot spot for the final time step that has never previously been a statistically significant hot spot) (S3 - Results; appendix). A significant upward trend was observed in Austria, Italy, Turkey, Nepal, India, Pakistan, the Philippines, Indonesia, China, Japan, South of Mexico, Colombia, Brazil, the DRC, Sierra Leone and the USA (Figure 3 B).

This analysis for the 20-years' period revealed that the number of deadly landslides increased across the globe in 128 countries (Figure 1), showing that the number of landslides in the second half of the study period (2005-2014) was larger than the number of landslides in the first half (1995-2004). The Sign test indicates a significant difference (p-value=0.02) between the number of landslides in the first 10-years compared with the number in the second 10-years (Figure 6; appendix). There was an increasing trend towards more landslides and more extreme rainfall

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during 2005-2014 compared with 1995-2004 (Figure 4, and Figure 6; appendix). Statistical analysis corresponds to the exact Wilcoxon-Mann-Whitney and Kruskal-Wallis tests, the first one is a special case of the latter one for comparing two samples. All the p-values obtained clearly indicate that there is a highly significant trend both in the 10-year and in the 5-year periods (Table 3. appendix).

The Northern Pacific (S1 Terminology, appendix), Southern Pacific, South America, and Western Europe, experienced extreme rainfall events (Figure 5). Using the historical rainfall and landslide datasets, empirical rainfall threshold values were established for different regions. The results indicated that in Africa, for example, a cumulative rainfall threshold of 25 mm is necessary to trigger landslides. Other observed regional threshold values were: 26 mm in North America, 55 mm in the North Pacific, 22 mm in South Asia, 49 mm in Southeast Asia, 38 mm in East Asia, and 11 mm in Central Eurasia (Figure 7, appendix). This empirical approach is based on the previous literature suggesting a strong correlation between rainfall and landslides.[21-23]

Nearly 60 % of the landslides happened when rainfall exceeded the 90^{th} percentile of the empirical rainfall distribution for 2-days accumulations in the previous 20 years (Table 2). However, 12% of the locations that suffered from landslides did not exceed the 50^{th} percentile of rainfall (Figure 8, appendix). The percentage of landslides that coincided with extreme rainfall ($\geq$ 90^{th} percentile)[24] increased in the second decade of the study period. This suggests that the number of deadly landslides and more frequent extreme rainfall events striking populated areas, are associated.

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Figure 6 provides the contours of a 2D (binned) probability density of the joint distribution of casualties/population and the amount of rainfall in mm. There are three different classes of patterns: class one, comprising Africa, Europe, and South America, shows densely concentrated contours, with relatively low numbers of both casualties and rainfall. Class two (Oceania and Asia) exhibits less concentrated contours, with a lower number of casualties and higher rainfall values than class one. Finally, North America (class three) shows a bimodal pattern (two peaks) where the contours around the first mode (at 25 mm rainfall) are similar to those of class two, the contour around the second mode (located at 140 mm rainfall) demonstrates that rainfall values higher than 130 mm are significantly more probable than for class two members, whereas such high values are improbable for class one.

Figure 7 adds to the analysis of Figure 6. The six shingles are ordered by increasing rainfall values, they are partly overlapping and the first one refers to the lowest rainfall values and the last one to the highest values. Asia presents the highest values of casualties for the two shingles on the left (lower RI), thus suggesting that rainfall is usually the trigger for fatal landslides and also that the impact it causes should be directly dependent on the population distribution. Europe presents regular values of casualties (on average, half of the ones for Asia) for all ranges of RI; more than 400 casualties only occur with high rainfall values. North America presents a similar behavior but has cases reaching a higher number of casualties. For Africa and Oceania regions the behavior is similar to Europe, essentially, the number of casualties remains below 300, albeit in exceptional cases it may reach a higher number of casualties. For South America, it is the shingle at the right side (higher RI) that correlates with the highest damages in population.

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Discussion

Previous studies that have investigated landslide fatalities and casualties have described how challenging it is to create reliable inventories that provide good estimates based exclusively on landslide deaths.[9-11] Compared to previous studies (recorded landslides events in 7 and 12 years of time without verification at the country level)[9,11], this research provides better estimates because landslide fatalities on a global scale were analyzed for a longer period of 20 years (1995 to 2014) and 89.6% records of 3876 landslide events were verified.

Our results indicate that yearly more than 4,000 people are killed by landslides alone and over 7,800 further deaths are caused by other natural hazards that typically trigger landslides as well (Table 1). Based on our new dataset, GLS-DAT, landslides are thus should be ranked as the 4th biggest killer globally among natural disasters, after floods, storms, and earthquakes.[7]

In terms of geographical distribution of deadly landslides, our finding (Figure 2) is consistent with previously published studies (Figure 5, Petley 2012)[11] but shows more landslides in Southern Europe, Eastern Australia, and China. The annual number of deadly landslides is increasing over the study period, with more landslides between 2005-2014. The strong seasonality exhibited during the summer and autumn reflects the preponderance of rainfall-induced landslides in the Northern and Southern Hemispheres, particularly during South Asia's summer monsoon. In equatorial countries, where seasonal rainfall variations are less, deadly landslides occur throughout the year.

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These results also reveal that landslide hotspots (Figures 3A and 3B) and extreme rainfall (Figure 5) co-occur at medium spatial scales and may be related to rainfall changes across the globe. Our data analysis indicates that 1999, 2005, 2008 and 2013, all had unusually high numbers of deadly landslides (Figure 1) and associated primary hazard than other years (Figure 9; appendix). The number of natural disasters has increased nearly three-fold, between 2000 to 2009 considering 1980 to 1989.[25] This growth has been primarily due to a rise in the number of climate-related extreme rainfall accounting for nearly 80% of the increase. This is consistent with our findings, as trends in geophysical occurrences, such as earthquakes and volcanic eruptions have remained stable.[25] The rainfall data trends for the first decade studied showed reductions in extreme rainfall events in Africa, Central Eurasia, the Himalayas, North America, the North Pacific, and South and South Eastern Asia, but increasingly erratic variations in extreme rainfall events in Central Eurasia and the Southern Pacific regions. The data for the second decade revealed a marked increase in extreme rainfall events, especially for the Northern/Eastern Hemispheres: intense rainfall events were more frequent for Central Eurasia, Northern Pacific, and South Asia in 2013-2014. There were also several extreme rainfall event years (2003 and 2009-2010) in Southeast Asia, Africa, and South America. Extreme rainfall generally increased during 2005-2014 and this trend is projected to continue.[15,26,27]

Extensive records of landslide occurrence in West Africa, South Pacific, East Asia and Central Eurasia show that landslide prediction may be closely related to the probability of exceeding threshold values of rainfall a few days prior to the landslide (Figure 7; Appendix). This was also proved to be possible in other regions worldwide, namely part of the Caribbean, where regional rainfall patterns were established as triggering landslides.[5]

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Although the majority (60 %) of landslides are associated in time and place with extreme rainfall events, our results also showed that nearly 12 % of the landslide locations did not experience excess rainfall (>50th percentile) (Figure 8; appendix) and must thus have been triggered by other contributing factors, like human activities, snowmelt etc., that because of the scale of this study were not taken into account. The new data presented shows a substantial increase in the number of landslides, especially those with high casualty rates, in newly emerging industrialized countries such as China, India, Indonesia, Malaysia, Thailand, Brazil, Mexico and Turkey. Increasing population density, rapid urbanization, the construction of infrastructure, such as railways and highways, industrial development, and the development of previously preserved mountainous terrain, including deforestation, have brought human settlements into high risk areas.[28-30]

Worldwide, approximately 1.5 million km^2 of forest was lost from 2000 to 2012.[31] Extensive forest loss (1021 km^2/year) suggests deforestation may be another contributing factor, along with extreme rainfall events, in the increasing number of deadly landslides in Indonesia and Brazil. Forest fires in the intermountain West of North America and in European countries, such as Spain, contribute to a complicated dynamic of deforestation and landslide events; the same study also revealed high incidences of landslides in recent years in Brazil, Bolivia, Cambodia, Malaysia, the Cote d'Ivoire, and Tanzania, all of which were associated with a significant loss of forest cover.[31] High population distributions across space are another key contributing factor driving the high casualty rates in countries in East Asia, South America and the North and South Pacific.

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There are a few limitations in the study. First, our study did not take into account the conditioning causes of landslides like geology, relief, soil moisture conditions, land use and land cover, anthropogenic modifications or tectonic weakening of hill slopes, and they may either strengthen or weaken the associations identified here before. Instead, we focused on global rainfall/ landslide patterns as well as population distributions. In addition, the information held in GLS-DAT is also likely to have underestimated the true number of casualties caused by landslides yearly, particularly by under-reporting smaller landslides or those that occurred in remote locations. The use of satellite based rainfall data may also have had an impact on the results' accuracy, but a global analysis must rely on an Earth Observation data set. However, we believe that this work will be helpful in contributing for the awareness of some societies in understanding the global patterns of landslides associated with rainfall changes and extreme weather events and the necessity to specialists embrace larger scale studies in some regions of the world. It is our hope that this also helps in establishing the solid platform toward strengthening the urban resilience to landslides.

Conclusion

The findings of this study demonstrated that there is a statistically significant increase in the number of fatal landslide events over the two decades evaluated for the 128 countries evaluated. The results provide also preliminary baseline information demonstrating a significant spatial and temporal linkage between deadly landslides and preceding extreme rainfall events, especially those located near populated areas (urbanized areas, major infrastructures) where the death toll is likely to be higher. This association holds at a global scale. The proportion of landslides attributed to extreme rainfall did not change across the 20-year period, but their absolute number

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increased in step with the increasing occurrence of extreme rainfall events. Climate change is expected to increase the frequency and intensity of such climatic events, which in conjunction with population growth, deforestation, rapid urbanization and unplanned development of mountainous terrain is likely to increase landslide-associated casualties worldwide. This study also provides useful information that is expected to alert policymakers and planners of some regions to seek ways to protect human lives and property more effectively in the future.

Figure legends

Figure 1. Fatalities and casualties due to landslide in the period of 1995-2014 (black bar specifies total fatalities while white bar indicates total casualties and, from the right axis, blue line shows the total number of landslides yearly).

Figure 2. Spatial distribution of casualties (death, injury, and missing) from landslides (A. 1995 – 1999, B. 2000 – 2004, C. 2005 – 2009, D. 2010 – 2014)

Figure 3 A: Geographic clusters of deadly landslides

Figure 3 B: Location specific trend of landslides

Figure 4. Trend of yearly landslides and percentile of rainfall (millimeter)

Figure 5. Spatial distribution of extreme rainfall in landslide locations (only >90th percentile are shown)

Figure 6: Association between rainfall intensity, casualty, population distribution and landslides' impact for five continents

Figure 7: Association between casualty, population distribution and precipitation intensity for five continents

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Author contributions

Ubydul Haque conceived the study design, prepared the database, analyzed the data, and drafted the manuscript. Jürgen Pilz contributed to the methodology. Paula F. da Silva, Peter Andersen, and Graziella Devoli contributed in drafting the manuscript. Asmaa khaloua, Bingxin Zhao, Wahyu Wilopo, Lu Ping, Juneseok Lee, Taro Yamamoto, David Keeling, and Jianhong WU contributed in database preparation and writing.

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Table 1

		Primary hazards				
	Only Landslide	**Flood**	**Storm**	**Earthquake**	**Others***	**Total**
Deaths (a)	85,013	42683	24347	4052	172	156,267
Injured people (b)	12,737	164	107	626	98	13732
Missing people (c)	6013	1165	46	287	26	7537
Casualties (a+b+c)	103,763	44012	24500	4965	296	177536
Total number of events	3652	78	24	90	32	3876
Average number of fatalities per event	~23	~547	~1014	~45	~5	~40
Average number of casualties per event	~28	~564	~1021	~55	~9	~46
Yearly killed by landslides alone						~4000
Yearly killed by landslides and other associated non-separable disasters						~7800

* Cliff collapse, train derailment due to landslide, sea erosion and landslide during construction work

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Table 2

	50^{th}	75^{th}	90^{th}	95^{th}	99^{th}
1-day	88	77	57	42	16
2-day	88	78	60	45	19
3-day	87	76	57	43	18

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***Highlights**

- The research herein presented hypothesize that climate change associated extreme rainfall and population distribution, will contribute to a higher number of deadly landslides worldwide.
- This study maps spatially identifies deadly landslides in 128 countries and it encompasses their role, for a 20 years' period January/1995 to December/2014, considered representative for establishing a relationship between landslides and their meteorological triggers.
- A hot spot analysis for the daily record of landslide locations was performed, as well as a percentile-based approach to evaluate the trend of extreme rainfall events for each occurrence.
- The relationship between casualty and population conditioning on the rainfall values was also evaluated. For 20 years, 3876 landslides caused a total of 163,658 deaths and 11,689 injuries globally.
- A significant global rise in the number of deadly landslides and hotspots across the studied period was observed. Analysis of daily rainfall confirmed that more than half of the events were in areas exposed to the risk of extreme rainfall.

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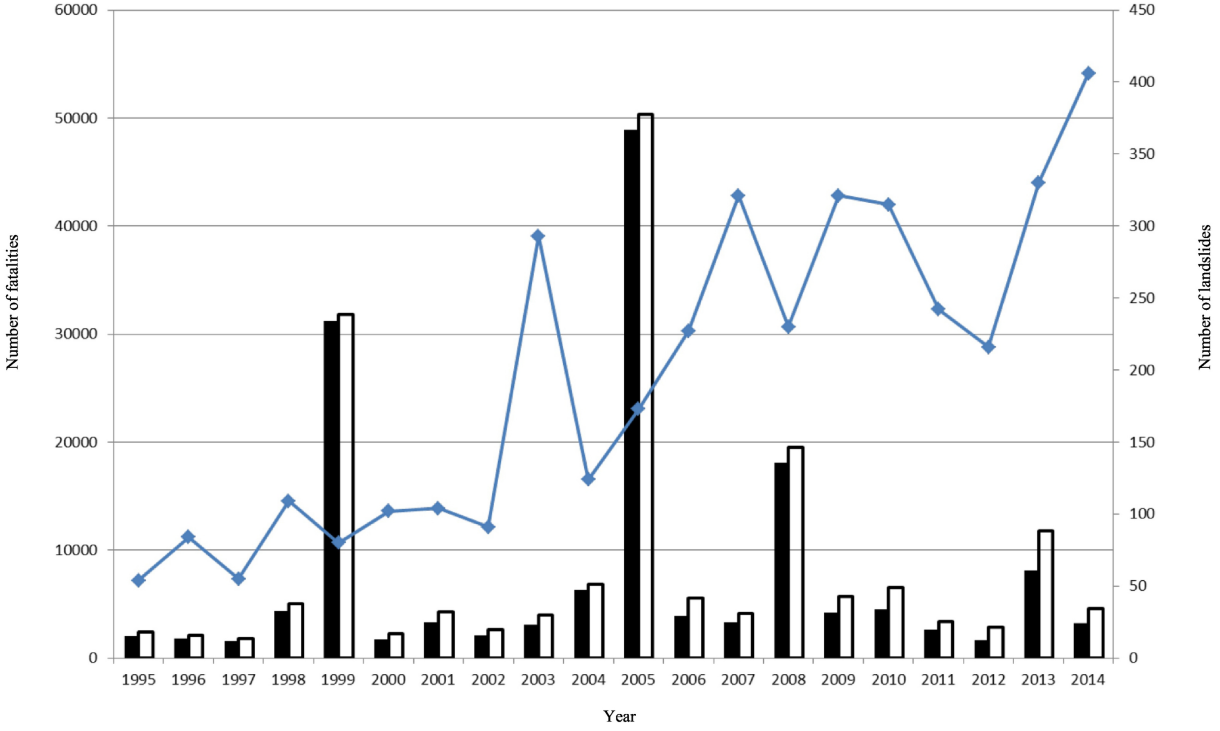

60000
50000
40000
30000
20000
10000
0
Number of fatalities
450
400
350
300
250
200
150
100
50
0
Number of landslides
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
Year

Figure 1

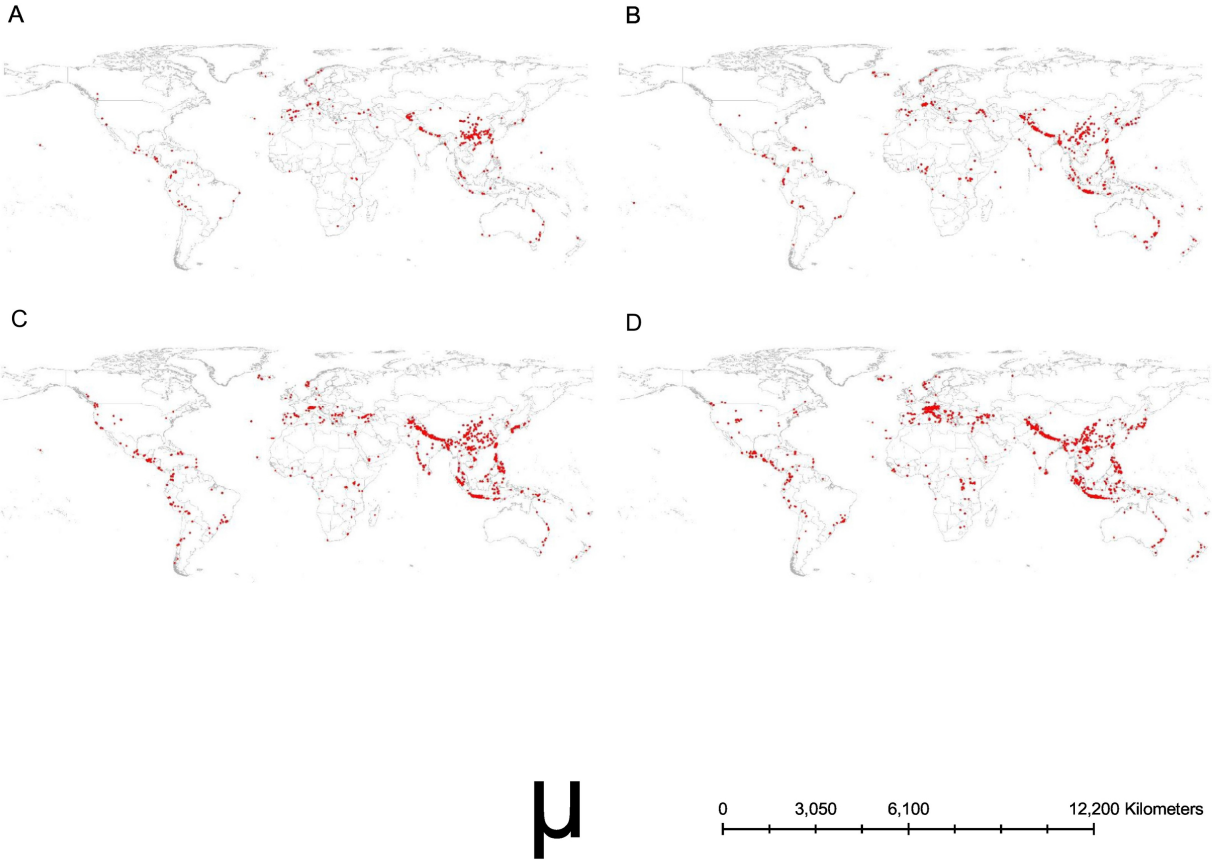
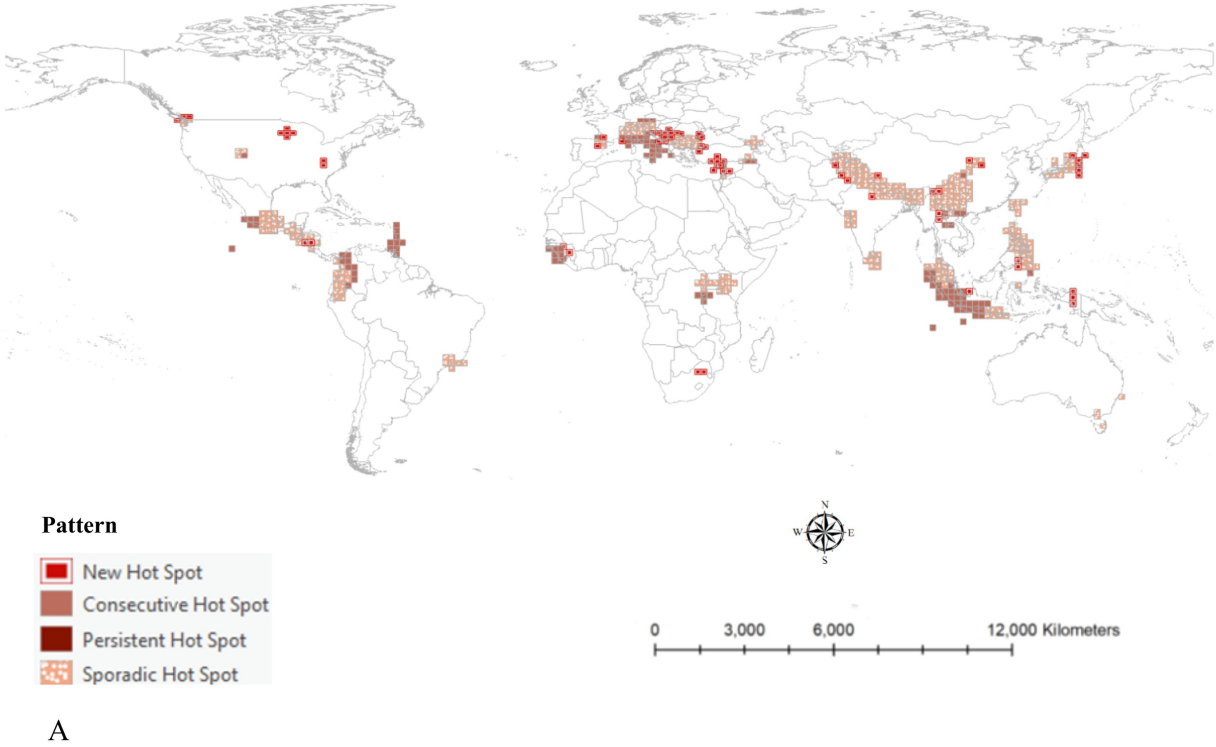
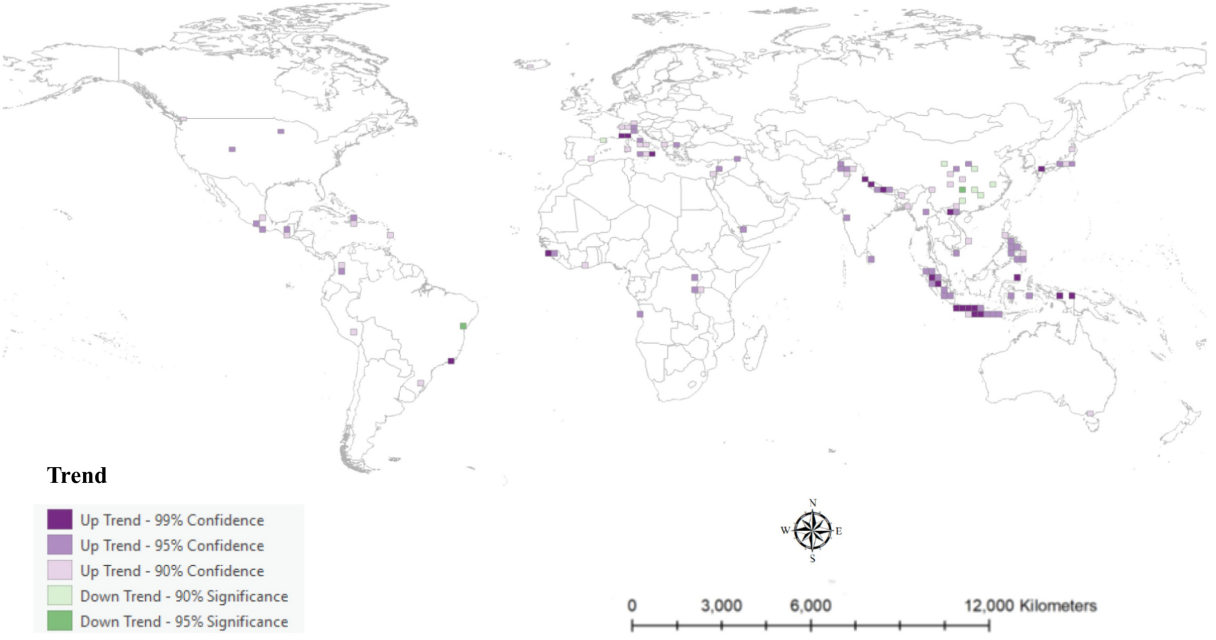


Figure 2


Pattern
New Hot Spot
Consecutive Hot Spot
Persistent Hot Spot
Sporadic Hot Spot
N
W
E
S
0
3,000
6,000
12,000 Kilometers

A


Trend
Up Trend - 99% Confidence
Up Trend - 95% Confidence
Up Trend - 90% Confidence
Down Trend - 90% Significance
Down Trend - 95% Significance
N
W
E
S
0
3,000
6,000
12,000 Kilometers

B

Figure 3

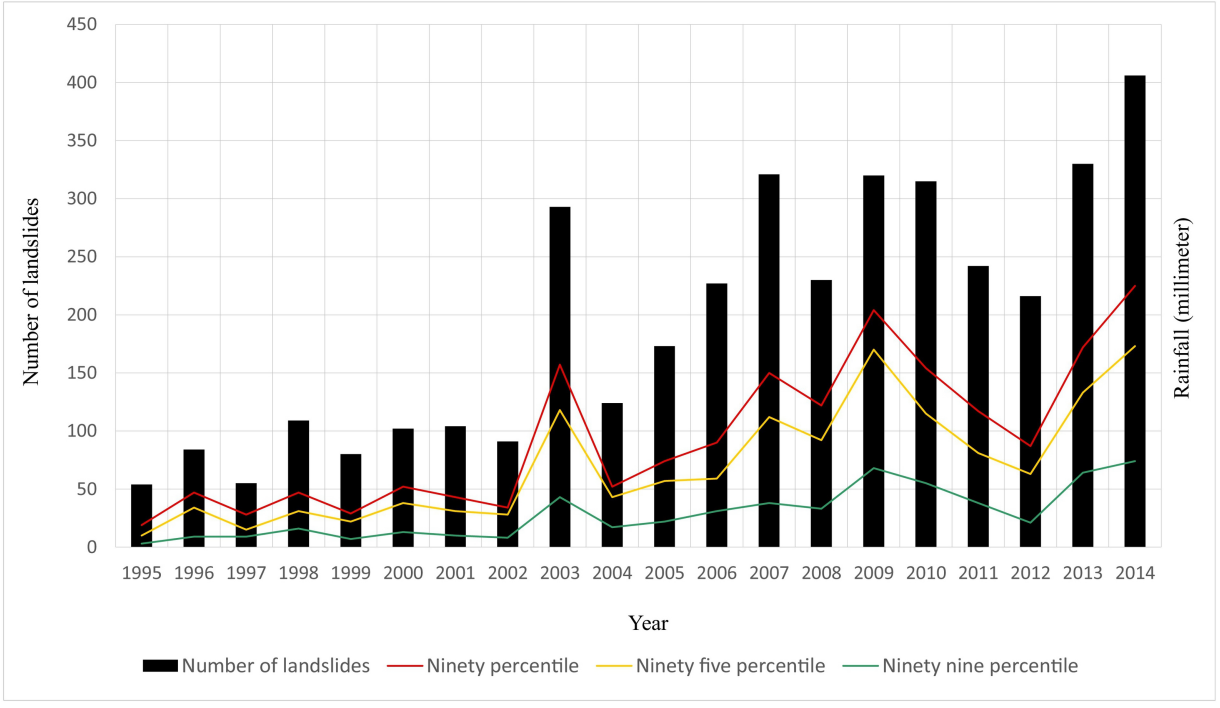

Number of landslides
Rainfall (millimeter)
Year
450
400
350
300
250
200
150
100
50
0
1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014
Number of landslides
Ninety percentile
Ninety five percentile
Ninety nine percentile

Figure 4

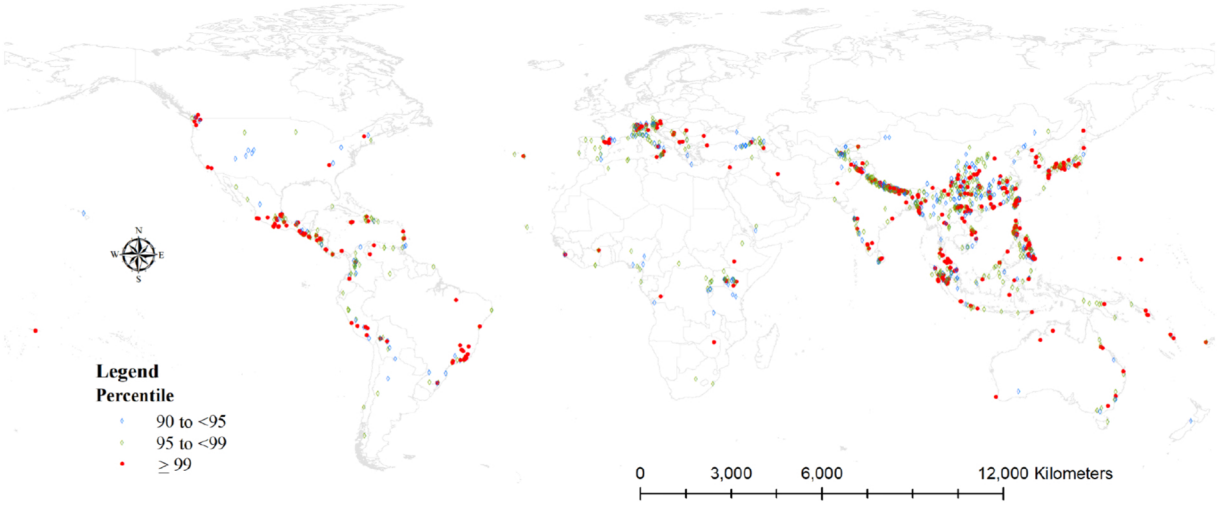

N
W
E
S
Legend
Percentile
90 to <95
95 to <99
≥ 99
0
3,000
6,000
12,000 Kilometers

Figure 5

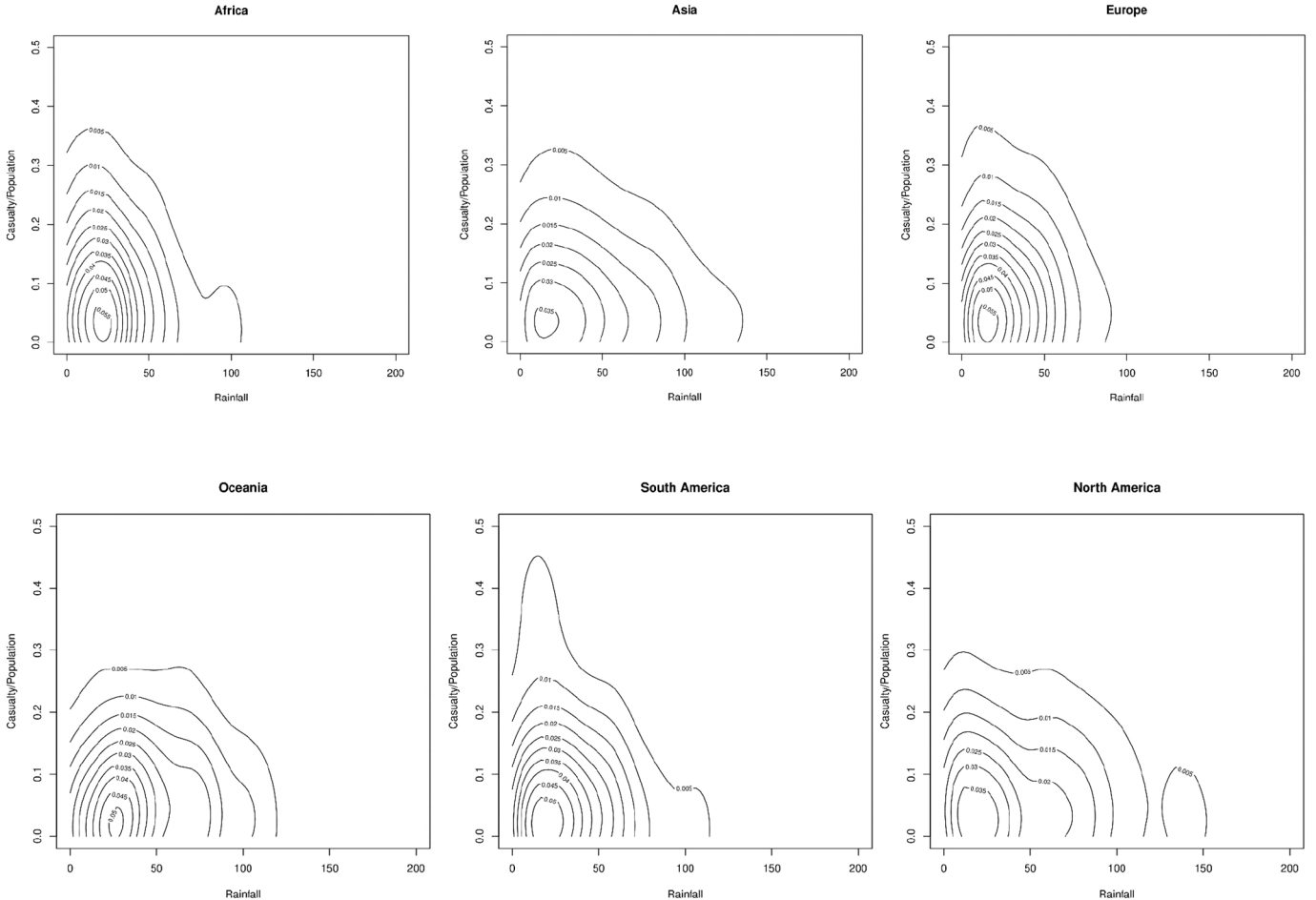
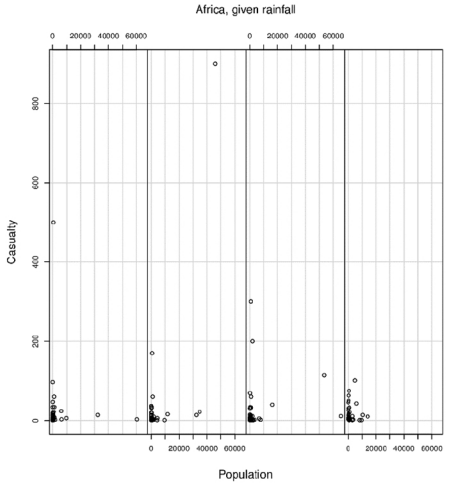
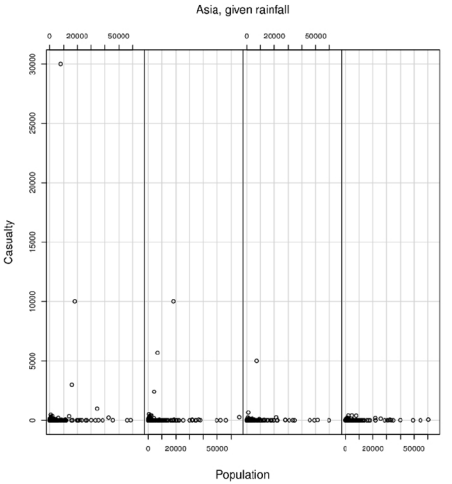
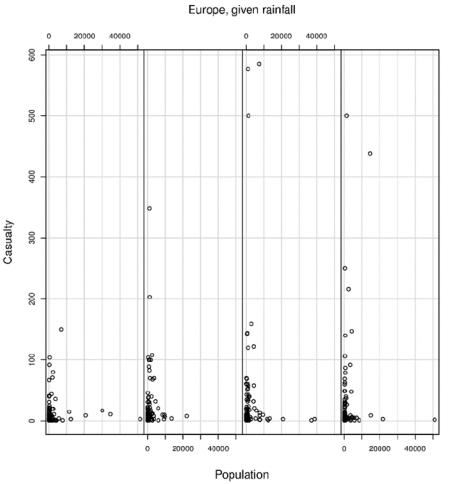
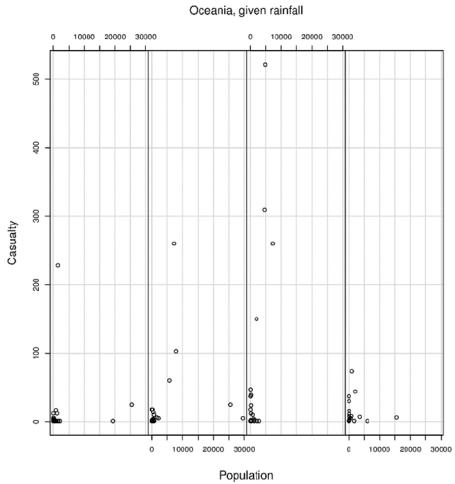

Africa
Asia
Europe
Oceania
South America
North America
Casualty/Population
Rainfall
0.0
0.1
0.2
0.3
0.4
0.5
0
50
100
150
200

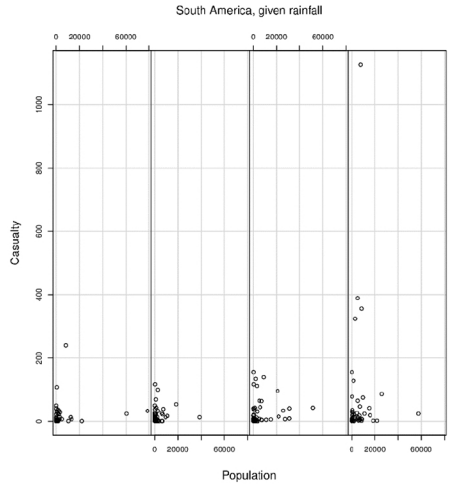
Figure 6


Africa, given rainfall
Casualty
Population


Asia, given rainfall
Casualty
Population


Europe, given rainfall
Casualty
Population


Oceania, given rainfall
Casualty
Population


South America, given rainfall
Casualty
Population

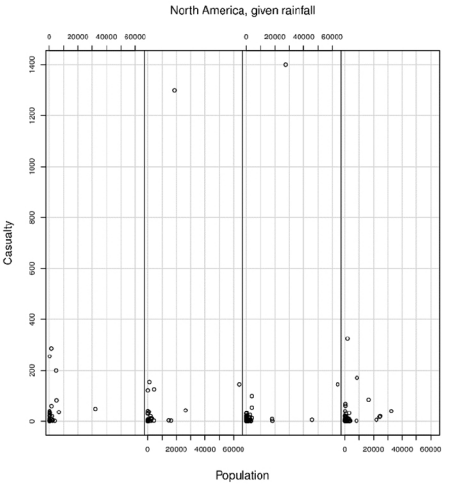

North America, given rainfall
Casualty
Population

Figure 7